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Thermal transfer in extracted incisors during thermal pulp sensitivity testing

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Abstract

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Aim To measure the temperature distribution within tooth structure during and after application of thermal stimuli used during pulp sensitivity testing.

Methodology Extracted intact human maxillary anterior teeth were investigated for temperature changes at the labial enamel, the dentino-enamel junction (DEJ) and pulpal surface during and after a 5-s application of six different thermal stimuli: hot water (80 °C), heated gutta-percha (140 °C), carbon dioxide dry ice (−72 °C), refrigerant spray (−50 °C), ice stick (0 °C) and cold water (2 °C). J-type thermocouples and heat conduction paste were used to detect temperature changes, together with a data acquisition system (Labview). Data were analysed using analysis of variance, with a confidence level of $P < 0.05$.

Results Temperature change was detected more quickly at the DEJ and pulpal surface with the application of hot water, heated gutta-percha and refrigerant spray than with carbon dioxide dry ice and ice ($P < 0.05$). Cold water and refrigerant spray were in the same range in terms of time to detect temperature change at both the DEJ and pulpal surface. Thermal stimuli with greater temperature difference from tooth temperature created a greater thermal gradient initially, followed by a greater temperature change at the DEJ and the pulpal surface. In this regard, ice and cold water were weaker stimuli than others ($P < 0.05$).

Conclusions Thermal stimuli used in pulp testing are highly variable in terms of temperature of the stimulus, rate of thermal transfer to the tooth and extent of temperature change within tooth structure. Overall, dry ice and refrigerant spray provide the most consistent stimuli, whereas heated gutta-percha and hot water were highly variable. Ice was a weak stimulus.

Keywords: heat, teeth, temperature change, thermal pulp sensitivity testing.

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Introduction

Thermal testing is routinely conducted clinically to assess pulp status. Various thermal stimuli in the range of temperature between −72 °C (carbon dioxide dry ice) and more than 100 °C (heated gutta-percha) have been used (White & Cooley 1977, Trowbridge *et al.* 1980, Fuss *et al.* 1986). When a thermal stimulus is applied on the labial enamel surface of a tooth with a healthy pulp, the patient senses a sharp pain that is localized to the tooth tested. Trowbridge *et al.* (1980) reported that patients sensed pain before there was a temperature change in the region of the pulpo-dentine junction (PDJ) where most sensory nerve endings are located. This observation is, however, readily explained by the hydrodynamic hypothesis: when the temperature change reaches dentine, thermal expansion or contraction of fluid within dentinal tubules causes fluid movement, which in turn triggers a nerve impulse (Pashley *et al.* 1983, Hashimoto *et al.* 2004).

Clinically, many different types of thermal stimuli have been used. Most are applied to the labial surface of enamel, but in cases of difficult diagnoses teeth may be flooded with hot or cold water over the entire crown (White & Cooley 1977). Both hot and cold

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stimuli are used, ranging from an ice stick (0 °C) to dry ice (−72 °C) or refrigerant (∼ −50 °C) sprayed onto a cotton pellet; heat is commonly applied in the form of heated gutta-percha (120–140 °C) or via an electrical heat source. The temperature and duration of the test are often not well controlled, and little information is available regarding the magnitude of the stimulus in terms of the rate and extent of the temperature change produced. As a result, thermal pulp testing is somewhat variable, with a degree of subjectivity in distinguishing a normal from an abnormal pulpal response. In the clinical situation, a number of questions have not been properly answered: for example, why are carbon dioxide dry ice (−72 °C) and refrigerant spray (−50 °C) more effective than an ice stick (95% vs. 30% accuracy respectively) (Fuss *et al.* 1986)? Why does carbon dioxide dry ice take a longer time to trigger a response than refrigerant spray, despite the greater temperature differential (Fuss *et al.* 1986, Jones *et al.* 2002)?

When a thermal stimulus is applied to the tooth, heat/cold is predominantly transported by conduction. The heat/cold flow will be determined by the thermal diffusivity both of the material providing the stimulus and the tooth. It has been reported that enamel has a higher value of thermal diffusivity than dentine (4.7 and 1.8×10^{-3} cm^2 s^{-1} respectively) (Brown *et al.* 1970). The heat capacity and thermal conductivity of the test materials have received little attention. It is reasonable to assume that there are large differences amongst materials both in the temperature difference between test material and tooth structure as well as in the rate of heat transfer to or from the tooth. Only very limited data on the temperature changes within intact teeth at various locations have been reported experimentally (Jacobs *et al.* 1973). Most studies of temperature changes were conducted using finite element analysis (Lloyd *et al.* 1978, Spierings *et al.* 1987a). Temperature measurement using extracted intact human teeth will provide some basic knowledge of the relative strength of different stimuli used in clinical endodontics.

The hydrodynamic theory currently offers the best explanation for thermal response in intact teeth and exposed dentine (Brännström & Johnson 1970, Trowbridge *et al.* 1980, Fuss *et al.* 1986, Jyvasjarvi & Kniffki 1987). Nonetheless, the relationship between the patients' sensation, temperature distribution within tooth structure and dentinal fluid flow has not been documented. It is generally accepted that a thermal stimulus causes dentinal fluid movement by the expansion or contraction of dentinal fluid, which in turn stimulates nerve fibres mechanically (Trowbridge *et al.* 1980, Hashimoto *et al.* 2004). It is likely that the dentinal fluid flow occurs only after the thermal stimulus reaches dentine (where dentinal fluid is located), so that the patient's response will be observed after the thermal stimulus reaches the dentino-enamel junction (DEJ). Thus, the DEJ is the critical location that should be carefully investigated with regard to temperature change. To date, information from experimental studies regarding the temperature distribution within tooth structure during thermal pulp testing is limited to temperature changes at the dentine of the pulpal wall (White & Cooley 1977, Trowbridge *et al.* 1980, Augsburger & Peters 1981, Fuss *et al.* 1986).

This aim of this study was to investigate temperature change within extracted human incisors at various locations: namely, outer enamel, the DEJ and the pulpal surface of dentine, during and after the application of various thermal stimuli used during clinical pulp testing. The extent of temperature change and time to detect a temperature change at the observed locations were analysed quantitatively to compare the strength of different stimuli used during thermal pulp sensitivity testing. The hypothesis being tested was that the rate and extent of temperature change at the DEJ and the pulpal surface of dentine are not simply a function of the temperature differential between the stimulus and the tooth surface.

Materials and methods

Tooth selection and preparation

This project was approved by the Human Research Ethics Committee of the University of Melbourne. Ten extracted intact human maxillary anterior teeth were collected and stored in distilled water with addition of chloramine-T (1%) (Sigma-Aldrich Co., St Louis, MO, USA) at 4 °C until use within 3 months. No information was available regarding patient age or dental history. Teeth were sectioned 2 mm below the cemento-enamel junction. The pulp tissue was removed with tweezers. An opening was prepared on the palatal surface of the tooth crown to allow thermocouple installation. A small stainless steel pulp-bur was used to drill a hole from the pulpal surface into the labial dentine in the middle third of the tooth crown until the DEJ was reached. In our preliminary study, a carbon steel pulp-bur cut dentine effectively but not enamel, so that cutting ceased when reaching the DEJ (Fig. 1a).

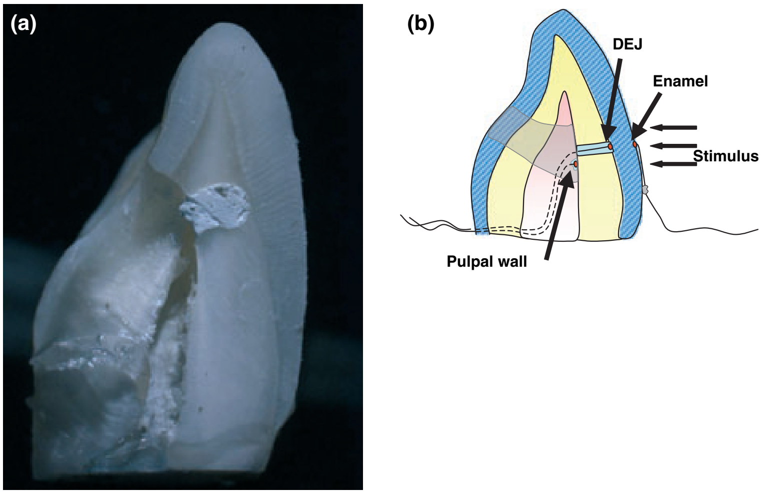

Figure 1 (a) Longitudinal section of human maxillary incisor showing the site of temperature measurement at the dentino-enamel junction (DEJ) (the drilled hole was filled with heat conducting compound). (b) thermocouples were installed at three locations, namely, the enamel, the DEJ and the dentine of pulpal wall.

Fine J-type thermocouples (No. 5TC-TT-J-40-36; Omega Engineering Inc., Stamford, CT, USA) were installed at three different approximately co-linear locations, namely, the enamel surface at the middle third of the tooth crown, the DEJ and the pulpal surface of dentine (Fig. 1b). Silicone heat conducting compound (Unick; Unick Chemical Corp., Taipei, Taiwan) was used to enhance the contact between the thermocouples and tooth structure. Thermocouples were connected to the data collecting system (Labview, National Instruments, Austin, TX, USA), which recorded the temperature changes at a sampling rate of 10 points per second.

The prepared teeth were then mounted on a thick glass slab using Epoxy resin (Araldyte; Selleys Pty Ltd., Padstow, NSW, Australia), and kept moist until testing.

Thermal stimulation

All experiments were conducted at room temperature (20 °C). Six different thermal stimuli were used: heated gutta-percha (~120–140 °C), hot water (80 °C), carbon dioxide dry ice (−72 °C), refrigerant spray (−50 °C) (Miracold Plus; Hager Worldwide, Inc., FL, USA), ice stick (0 °C) and cold water (2 °C). An attempt was made to standardize the diameter of most stimuli (~5 mm) in contact with the enamel surface. Gutta-percha was pre-fabricated into the form of a stick and mounted in a carrier. Immediately before use, the gutta-percha stick was heated in a flame until smoke was detected and then immediately applied on the tested tooth. Carbon dioxide dry ice was condensed into an insulated carrier with a 5 mm diameter. Refrigerant spray was sprayed on a cotton pellet comparable in size to the diameter of carbon dioxide dry ice and heated gutta-percha. The excess liquid on the cotton pellet was shaken off (as recommended by the manufacturer), and the soaked pellet was placed on the tooth. A tube with the same diameter as other stimuli (~5 mm) was filled with water and frozen. Hot water (80 °C) and cold water (2 °C) were continuously applied directly onto the enamel surface with a syringe. Each stimulus was applied on the middle third of the labial surface of the tooth crown for 5 s in random order with a 30-min interval between tests.

Data analysis

The baseline temperature over 60 s (before the application of thermal stimulus) was averaged. During and after the application of each thermal stimulus, the time to detect an increase/decrease in temperature from the averaged value was recorded as time *to detect a temperature change* (s). *The maximum temperature change* (°C) was the peak temperature recorded during and after thermal stimulation. *The maximum rate of temperature change* (°C s^{-1}) was obtained by averaging data over 1 s (10 points) which showed the greatest increase/decrease of temperature (which could be observed on the graph) during and after thermal stimulation.

Analysis of variance (ANOVA) was conducted to examine time to detect a temperature change, the maximum temperature change and the maximum rate of temperature change at the DEJ and the pulpal dentine surface. In cases where the variances were unequal, a logarithmic transformation was applied to the data before the ANOVA was performed. All pair-wise comparisons were made with the Tukey significant difference test, with a confidence level of $P < 0.05$.

Results

The patterns of temperature change within tooth structure at three different locations, namely, outer enamel surface, the DEJ and the pulpal surface of dentine during and after the application of six different thermal stimuli are illustrated in Fig. 2. When a thermal stimulus was applied on the enamel surface, a large temperature change at the outer enamel was observed almost immediately except with the application of carbon dioxide dry ice (Fig. 3), ice stick and heated gutta-percha that showed a lag period of approximately 0.5, 0.3 and 0.2 s, respectively, before the temperature increased/decreased suddenly to the approximate temperature of the stimulus. Heated gutta-percha did not provide constant temperature throughout its application of 5 s. The temperature dropped from its peak of 135 to 85 °C during the 5-s application. Heat/cold was transferred to deeper tooth structure resulting in a change of temperature at the observed locations (the DEJ and pulpal surface of

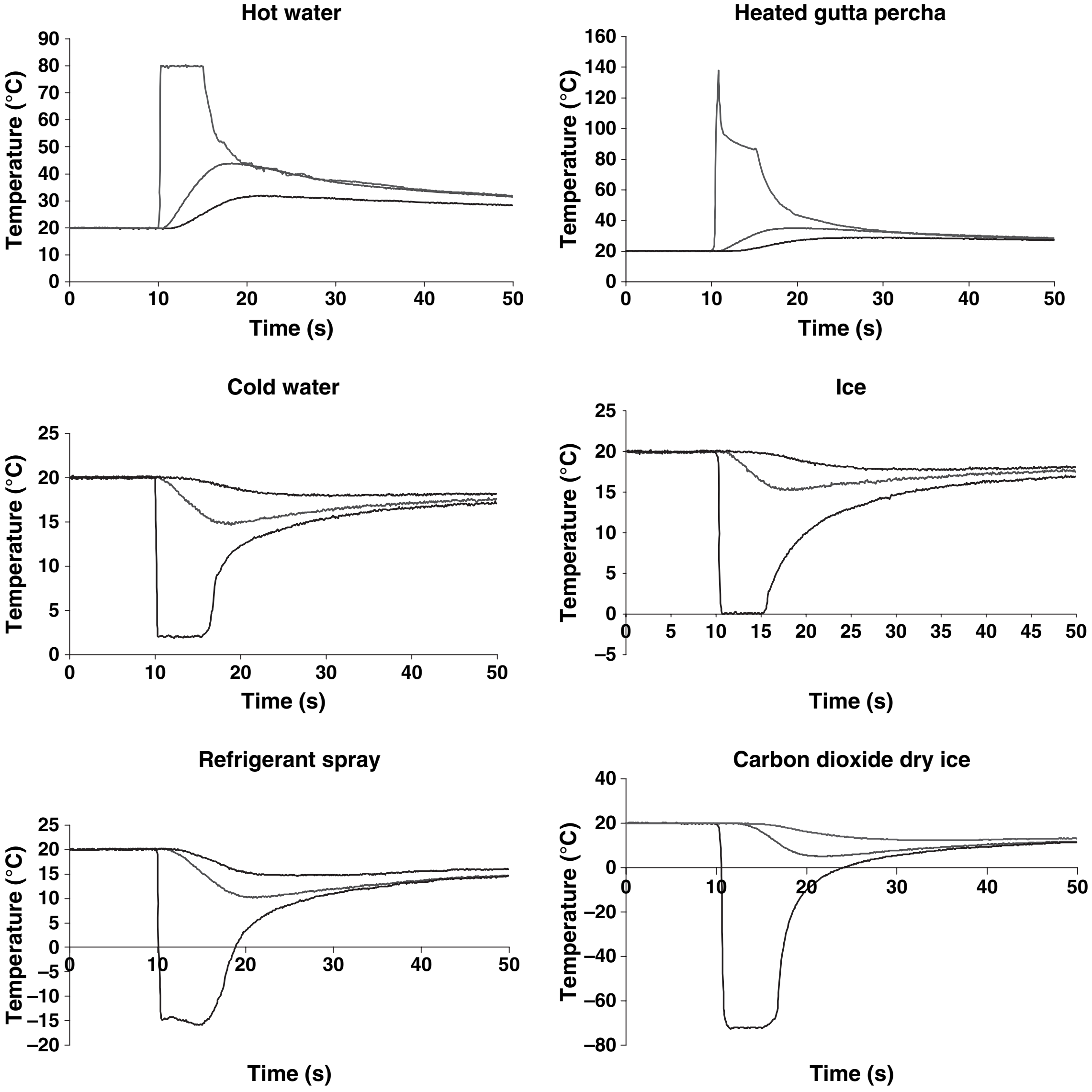

Figure 2 Temperature profiles within a tooth at three locations; namely, the enamel, the dentino-enamel junction and the dentine of pulpal wall during and after the application of six different thermal stimuli.

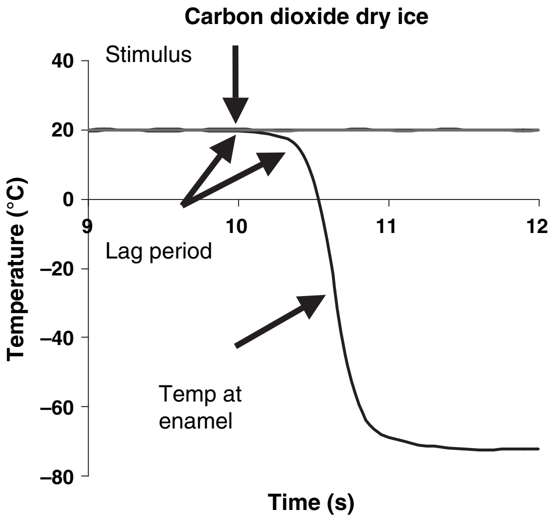

Figure 3 A lag period of 0.5 s was observed before the temperature of the enamel decreased suddenly to the temperature of carbon dioxide dry ice.

Table 1 Time (in s ± SD, $n = 10$) to detect a change in temperature during and after the application of six different thermal stimuli

Stimulus	Time to detect a change in temperature at the dentino-enamel juncation (s)	Time to detect a change in temperature at the dentine of pulpal wall (s)
Cold water	1.1 (0.1)	3.4 (0.3)
Ice	2.2 (0.2)	4.7 (0.3)
Refrigerant spray	1.2 (0.1)	2.7 (0.1)
Carbon dioxide dry ice	2.1 (0.1)	4.5 (0.2)
Heated gutta-percha	1.1 (0.1)	2.8 (0.1)
Hot water	0.7 (0.1)	2.2 (0.2)

dentine). The temperature continued to change at the DEJ and pulpal surface of dentine even after removal of the stimulus. Later, temperature at both locations returned gradually to baseline, together with the enamel surface.

The summarized data are presented in Tables 1 and 2. It took a longer time to detect a temperature change at the DEJ with carbon dioxide dry ice and ice application in comparison with other stimuli ($P < 0.05$). The maximum temperature change and the maximum rate of temperature change at the DEJ were less with cold water and ice application ($P < 0.05$). However, there was no statistically significant difference in the maximum rate of temperature change at the DEJ between cold water application and refrigerant spray. A temperature change was detected at the pulpal surface of dentine more slowly with carbon dioxide dry ice and ice than with heated gutta-percha, hot water and refrigerant spray application ($P < 0.05$). Cold water and ice caused a smaller temperature change at the pulpal surface of dentine with a slower rate of temperature change than other stimuli ($P < 0.05$).

Discussion

The mechanism by which the teeth sense a thermal stimulation has been studied for decades. Dentinal fluid movement as the result of temperature changes within tooth structure has been demonstrated to be involved in the sensory response mechanism (Brännström & Johnson 1970, Trowbridge *et al.* 1980, Andrew & Matthews 2000, Chidchuangchai *et al.* 2007). Nonetheless, little is known about the pattern of thermal transfer between the stimulus and the tooth or about the temperature change profile within tooth structure. This study was designed to investigate the temperature distribution within tooth structure and compare the strength of thermal stimuli used during thermal pulp vitality testing. Several conditions differed from the *in vivo* situation, including a difference in the environmental temperature (20 °C rather than 37 °C), the absence of a blood supply, soft tissue contents of the pulp chamber and periodontal ligament, as well as other unknown factors. Under the controlled conditions of this experiment, the strength of six different thermal stimuli could be quantitatively compared in relation to each other, although the temperature differential between the stimulus and tooth surface would be different *in vivo*.

To standardize thermal pulp testing for clinical use (to minimize variables between tests), the temperature of stimuli should be well controlled and reproducible. In routine clinical practice, gutta-percha is heated in a flame until smoke is observed, which can be very subjective. In this study, heated gutta-percha did not provide a consistent temperature (temperature varied between tests from 90 to 140 °C), which might be dependent on how long gutta-percha was heated in the flame and also how immediate the application was to the enamel surface. The low heat capacity of gutta-percha is shown by the decrease in temperature (~ 50 °C) during the 5-s application to the tooth surface. In preliminary studies, the application of a cotton pellet with the refrigerant spray caused a drop in enamel surface temperature from −50 to −10 °C, possibly depending on the amount of liquid on the

Table 2 The maximum temperature changes and the maximum rate of temperature changes at three locations: the enamel, the dentino-enamel junction (DEJ) and the dentine of pulpal wall (mean ± SD, $n = 10$)

		DEJ		Dentine of pulpal wall	
Stimuli	Peak temperature at the outer enamel surface (°C)	Maximum rate of temperature change (°C s^{-1})	Maximum temperature change (°C)	Maximum rate of temperature change (°C s^{-1})	Maximum temperature change (°C)
Cold water	2.1 (0.4)	1.05 (0.40)	5.8 (0.4)	0.35 (0.17)	2.5 (0.3)
Ice	0.4 (0.2)	0.84 (0.20)	5.2 (0.3)	0.26 (0.08)	2.1 (0.1)
Refrigerant spray	−17.2 (1.9)	2.19 (0.75)	12.5 (0.7)	0.67 (0.33)	5.9 (0.6)
Carbon dioxide dry ice	−70.3 (2.7)	2.93 (0.43)	17.0 (1.0)	0.93 (0.54)	7.8 (0.9)
Heated gutta-percha	120.8 (13.0)	4.23 (1.49)	22.0 (1.4)	1.21 (0.51)	8.7 (0.8)
Hot water	78 (1.2)	3.94 (1.34)	19.9 (1.1)	1.49 (0.77)	10.0 (1.0)

DEJ, dentino-enamel junction.

cotton pellet. If the excess liquid on the pellet was shaken off (as recommended by the manufacturer), the temperature was fairly consistent at approximately −20 °C in this study. The temperature of both hot and cold water is also likely to be poorly controlled in a clinical setting.

As mentioned by Jacobs *et al.* (1973) and Lloyd *et al.* (1978), the heat transfer rate between two materials is influenced by the surface area, the temperature difference and the heat transfer efficiency. When a tooth is subjected suddenly to a different temperature, time is required for heat transfer to occur. In general, the heat transfer from fluids will be greater in comparison with solid materials of the same temperature (Spierings *et al.* 1987b). This might explain an observation of a definite lag period with carbon dioxide dry ice, and to a smaller extent ice and heated gutta-percha application respectively. This observation was partly supported by Fuss *et al.* (1986), who commented that, in the case of carbon dioxide dry ice application, poor contact and vapour formation between thermal stimuli and tooth structure retarded temperature change.

It has been well documented that patients' sensation to thermal stimulation is from physical change in dentine rather than direct nerve stimulation (Trowbridge *et al.* 1980). It is likely that the patient's response is associated with the movement of dentinal fluid as the result of thermal expansion/contraction of dentinal fluid after the temperature change reaches the DEJ. Both the rate and magnitude of temperature change at the DEJ and the pulpal surface of dentine might influence the rate of dentinal fluid expansion or contraction and hence the rate of dentinal fluid flow and strength of the hydrodynamic force. The rate of temperature change has been shown to be critical; a more pronounced patients' response was detected when a rapid temperature change was achieved (Matthews 1977, Narhi *et al.* 1982a,b). Again, the different thermal stimuli varied substantially in terms of the time for a detectable temperature change at the DEJ (0.7–2.2 s) and pulpal surface (2.2–4.7 s). Surprisingly, dry ice was perhaps the slowest stimulus to produce a temperature change at both locations, although it resulted in a large change after the initial lag period. Ice was the weakest stimulus in this regard.

Temperature changes at the pulpal wall after thermal pulp testing have been studied by several researchers (White & Cooley 1977, Augsburger & Peters 1981, Fuss *et al.* 1986, Jones 1999). Data from the literature revealed an increase/decrease of temperature at the pulpal surface in the range 1–19 °C depending on experimental conditions such as tooth type, pulp contents, baseline tooth temperature and duration of thermal stimuli application. Temperature change at the pulpal surface of dentine, as measured experimentally, does not necessarily reflect temperature change in the pulp itself, with a high rate of blood flow and a dense capillary network immediately deep to the odontoblast layer. *In vivo*, temperature change within the dental pulp might be important in the diagnosis of irreversible pulpitis, involving stimulation of C-fibres deeper within the pulp. The experimental measurement of *in vivo* temperature within a vital pulp with intact circulation is impractical; in any case, temperature change within the pulp will depend on thermal transfer from dentine.

It is reasonable to assume, that a thermal stimulus that causes a greater temperature change and a greater rate of temperature change is considered a stronger stimulus than others. In this study, carbon dioxide dry ice, refrigerant spray, heated gutta-percha and hot water were in the same range, and ice was the weakest stimulus. Whilst hot water appeared to be a strong stimulus in this study, clinically it would have a much lower temperature differential, and the need to isolate the tooth with rubber dam makes it a less convenient routine test. The initial temperature is also likely to be poorly controlled in a clinical setting.

For routine thermal pulp sensitivity testing, carbon dioxide dry ice and refrigerant spray are considered more effective and reliable than ice (Fuss *et al.* 1986). The results of this study illustrated that the former stimuli caused a greater rate of temperature change and magnitude of temperature change at the outer enamel surface, the DEJ and the dentine of pulpal wall than the latter. The observation of delayed patients' response to carbon dioxide dry ice relative to refrigerant spray (despite its lower temperature) might be explained by the delayed heat transfer process.

Conclusion

1. The effectiveness of thermal stimuli used during pulp testing is governed not only by the temperature of the stimulus, but also by the efficiency of the heat transfer and the heat capacity of the test material.
2. Overall, carbon dioxide dry ice and refrigerant spray may be the stimuli of choice because of the well-controlled temperature and the large temperature differential. A definite lag period occurs before the rapid temperature change with dry ice.
3. Heated gutta-percha is a strong but less consistent stimulus in terms of both initial temperature and the temperature change during testing.
4. Ice is a weak stimulus compared with other cold tests.
5. Immersing teeth in either hot or cold water leads to rapid temperature change at the DEJ and pulpal wall, but the water temperature is poorly controlled and testing requires individual tooth isolation, which is cumbersome if multiple teeth are tested.

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